Chapter 6: How Forces Affect Motion

Redeveloped Edition | Class 9 Science | IESC Series

Original NCERT content reimagined with everyday Indian life examples, creative AI-enhanced exercises, and interdisciplinary insights.

Opening Wonder

It is 8:05 a.m. You are on the back of your friend's e-scooter, weaving through the lane behind your housing society, already late for the first bell. A stray dog darts out. Your friend slams the brakes.

You are thrown forward against their shoulders — even though neither of you touched the handlebar.

A few hours later, in the school nets, you watch the fastest bowler in your class release a cricket ball. The ball leaves the hand in a straight line, until gravity and air curve its path. That evening, on television, a badminton player smashes a shuttle so hard it seems to vanish before the opponent even moves their racket.

Three completely different scenes. One underlying question: **what actually changes an object's motion — and what keeps it going once it has started?**

In Chapter 4 (Motion), you learned to *describe* motion — position, velocity, acceleration. This chapter asks the deeper question: what *causes* motion to change at all? Why does the e-scooter lurch you forward when it stops, but not when it cruises at a steady speed? Why does a badminton shuttle slow down and drop, while a satellite orbiting the Earth just keeps going for years? Why does a canoeist pushing water backwards with a paddle end up moving forward?

By the end of this chapter you will be able to answer all of these — using just three laws written down by Isaac Newton in 1687, plus the everyday, overlooked force called friction. These three laws are not just exam material. They are quietly running in the background every time an ISRO rocket lifts off from Sriharikota, every time an airbag inflates in a car crash, and every time you catch a fast cricket ball without breaking your fingers.

6.1 The Concept of Force

You already know from earlier grades that a force can make a stationary object start moving, change the speed or direction of a moving object, or change its shape. A ball at rest starts rolling when you kick it; a bat changes the direction of a fast-moving cricket ball; your fingers squeezing a lemon change its shape to extract juice.

Notice something about how force is always described: it is never just "how much" — it is always **how much, in which direction**. "Friction acts opposite to the direction of motion." "Like poles of a magnet repel; unlike poles attract."

"The Earth pulls objects towards itself." Every one of these statements specifies a direction. This tells us something important:

Force is a physical quantity that has both magnitude and direction — exactly like the displacement, velocity, and acceleration you studied in Chapter 4.

The SI unit of force is the **newton**, written with a small "n" in full (newton) but a capital symbol: **N**. The magnitude of a force expresses its strength — how hard the push or pull is.

> **Everyday Connection: Force, All Around Your Morning**
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> Before you have even left home, you have already experienced a dozen forces: the force of your feet pushing the floor as you get out of bed, the force of gravity pulling the flap of your school bag shut, the force your thumb applies to unlock your phone, the frictional force letting your rubber slippers grip the bathroom floor. Physics is not a subject that starts when the bell rings — it is the reason your morning routine works at all.

6.1.1 Measuring the Magnitude of a Force

How do we actually put a number on a force? You may recall using a **spring balance** in an earlier grade to measure the weight of an object. Weight, remember, is simply the gravitational force with which the Earth pulls an object towards itself. A spring balance can measure not just weight, but the magnitude of any force — if you pull on its free hook, it measures the force with which you are pulling on the spring inside.

> **Everyday Connection: The Spring Balance in a Fish Market**
>
> Walk through any fish market in Kochi, Mumbai, or Kolkata early in the morning, and you will see vendors weighing the day's catch on a hanging spring balance (locally often called a **kanta**). The fish is hooked on one end; the vendor reads off the kilograms directly from how far the spring has stretched. That reading is a direct measurement of the gravitational force — the weight — pulling the fish downward. The same principle, at smaller scales, is what a science-lab spring balance does with a wooden block on your desk.

> **Thread of Curiosity: How Small Can a Force Get?**
>
> In everyday life, the smallest forces we can directly *feel* are of the order of millinewtons (10^{-3} N) — something like the light touch of an insect landing on your arm. But scientists, in specialised laboratory experiments, can now measure forces as small as **yoctonewtons (10^{-24} N)** — a number so tiny it is almost impossible to picture. That is roughly the gravitational pull one bacterium exerts on another sitting a metre away. Force, it turns out, has no natural "smallest size" — only the limits of our instruments.

6.2 Balanced and Unbalanced Forces

In the real world, it is rare for only one force to act on an object at a time. Usually, several forces act together. When you push a heavy school trunk across a hostel room floor, apart from your push, the force of friction also acts on the trunk, opposing the direction of motion. Or think of a paper boat floating on a puddle after monsoon rain — two forces act on it simultaneously: gravity pulling it down, and the buoyant force of water pushing it up.

So what happens when more than one force acts on an object at rest or in motion?

Everyday Connection: Tug of War at the Village Fair

Think of a tug-of-war contest at a school sports day or village fair. If both teams pull the rope with exactly equal force, the rope does not move at all — this is because the two forces are **equal in magnitude but opposite in direction**. We call such forces **balanced forces**.

The moment one team pulls even slightly harder, the forces become **unbalanced**, and the rope moves in the direction of the team applying the larger force. This is exactly the physics behind why a tug-of-war can stay perfectly still for several tense seconds, and then suddenly swing one way.

If the forces on an object are not balanced, a **non-zero net force** acts on it. When two forces act in opposite directions but with different magnitudes, the magnitude of the net force equals the *difference* between them, and its direction is along the larger force. When two forces act in the *same* direction — like two friends push-starting a stalled auto-rickshaw — the net force is the *sum* of the two, in that common direction.

Worked Example 6.1 — Redeveloped: Push-Starting an Auto-Rickshaw

Original book version: Two forces of 10 N and 6 N act on a block lying on a table, in three different arrangements. Find the net force in each case.

Everyday Version: An auto-rickshaw has stalled at a signal in three different traffic situations. In each situation, two people are pushing it with forces of 10 N and 6 N. What is the magnitude and direction of the net force on the auto in each case?

(a) Both push in the same direction (forward):

Net force = 10 N + 6 N = **16 N**, acting forward.

(b) One pushes forward (10 N), the other accidentally pushes backward (6 N):

Net force = 10 N − 6 N = **4 N**, acting in the direction of the 10 N push (forward).

(c) The 6 N push is forward, the 10 N push is backward (say, someone is pulling the auto back to stop it rolling downhill):

Net force = 10 N − 6 N = **4 N**, acting in the direction of the 10 N push (backward).

Creative Spark : If a third friend joins and pushes with 4 N in the same direction as the "losing" force in case (b) or (c), will the auto move? Work out the new net force yourself.

Ready to Go Beyond

Here, we have only considered forces acting exactly parallel or exactly opposite to each other. In situations where forces act at an *angle* to each other — like two people pulling a stuck cricket sight-screen from different corners — the net force must be found using vector addition, which you will study in higher grades.

There are also situations where equal and opposite forces act on the *two ends* of an extended object, making it rotate rather than move in a straight line — like turning a bicycle handlebar or a water tap with both hands. This turning effect (called **torque**) is also a topic for higher grades.

Pause and Ponder:

1. A weightlifter holds a loaded barbell steady above her head. List the two forces acting on the barbell. Are these forces balanced?
2. Two players are having an arm-wrestling match, and at one instant, both arms are tilted slightly towards one player. At that instant, are the forces the two players exert on each other balanced? If not, which player is applying the larger force?

6.3 The Force of Friction: Often Overlooked but Always Present

You met the force of friction in an earlier grade. Let us now understand it more deeply. Suppose a school bag is resting on the floor and you apply a gentle forward push. Does it move immediately? Often, it does not — you have to push harder before it budges. Why?

This happens because of the force of friction acting between the bottom of the bag and the floor, in a direction **opposite** to your push. The bag will only start moving once your applied force exceeds the force of friction, so that a net force finally acts in the direction of motion.

Note

Apart from the applied force and friction, two more forces act on any object resting on a surface: its **weight** (gravitational force, acting downward) and the **normal force** exerted by the surface (acting upward, perpendicular to the surface). These two are balanced and do not affect horizontal motion. Air also exerts a small frictional drag on moving objects, though this is often small enough to neglect.

Now think about what happens once an object is already moving. You stop pedalling your bicycle, and it gradually comes to rest. You stop pushing a carrom striker, and it slides to a halt. Does this mean a force must be continuously applied to keep something moving? **Not quite** — it means that on a moving

object, friction is continuously acting *against* the motion, and unless you keep countering it, friction alone will eventually stop the object.

🔬 Activity 6.1 — Redeveloped: The Carrom Coin Slide

Original book version: Flick a stack of four ₹10 coins across a stretched rubber band on a wooden table top, a laminated table top, and a marble/tiled floor, and compare how far the coins slide before stopping.

Everyday Version: Every carrom player knows that a striker glides beautifully on a boric-powder-dusted board, but drags and stops quickly on a bare, sticky board. Let's test this idea rigorously using the same method as the original activity — but framed around a game you already know.

Your task:

1. Take a stack of four identical coins taped together, a strong rubber band, and locate three different flat, level surfaces at home — a wooden study table, a laminated dining table, and a marble or tiled floor.
2. Stretch the rubber band between your thumb and forefinger. Mark points A and B where your fingers rest, and a further point C to which you will pull the band back each time.
3. Place the coin-stack near the midpoint of A–B. Pull it back to C using a finger of your other hand (like loading a carrom striker), then release.
4. Measure how far the coins travel from C before coming to rest. Repeat twice on each surface, keeping the pull-back distance (A to C) identical each time.

What you should notice: the coins travel a much shorter distance on the sticky laminate than on the smooth, polished marble floor. This tells you that the force of friction is different for different surface pairs — smaller on marble, larger on laminate. This is exactly why carrom players dust the board with boric powder: it fills in microscopic irregularities and reduces friction, letting the striker glide true.

🔬 Activity 6.2 — Redeveloped: Weighing Friction with a Spring Balance

Original book version: Attach a wooden block to a spring balance, and pull it with gradually increasing force across each of the surfaces from Activity 6.1, noting the reading when the block just begins to move.

Everyday Version: Attach a spring balance (or a luggage spring scale, like porters use at railway platforms to weigh trunks) to a wooden block or a filled pencil box. Place it on each of your three surfaces from Activity 6.1, and pull with slowly increasing force until the block just starts to slide.

The reading on the balance at that exact moment is an approximate measure of the force of friction between the block and that surface. You should find: the smaller the reading, the smaller the friction — and the surface with the smallest reading is the same one on which your carrom-coin stack (Activity 6.1) travelled the farthest. The two activities confirm each other.

Meet a Scientist: Galileo Galilei — Doubting What "Everyone Knew"

For ages, it was assumed that a force was needed not just to *start* an object

moving, but to *keep* it moving at all — after all, everything around us eventually stops. It was the Italian scientist **Galileo Galilei (1564–1642)** who, through a series of careful thought experiments in the 17th century, argued the opposite: if a body moves along a horizontal surface and every source of friction and resistance is removed, it would continue moving forever, at constant velocity, with no force needed at all.

This was a radical idea at the time — it meant that rest and constant-velocity motion were not fundamentally different states, an insight that Isaac Newton would later build directly into his first law of motion.

Meet a Scientist: Isaac Newton — The Three Laws of 1687

Sir Isaac Newton (1642/43–1727) used the word **inertia** to describe the tendency of objects to resist any change in their state of rest or of uniform motion — a tendency he had inherited conceptually from Galileo's thought experiments. Building on this idea, Newton framed his first law of motion, and alongside it, presented two more laws — together, published in 1687 in his monumental work, the ***Principia Mathematica***. The formulation of these three laws was a defining moment in the history of science, and the SI unit of force, the newton, is named in his honour.

Remember: when a unit is named after a person, its full name is written in lower case (*newton*, not *Newton*), while its symbol is capitalised (**N**, not n).

Thread of Curiosity: What If Friction Vanished Overnight?

Imagine waking up tomorrow to a world with zero friction anywhere. Your shoes would not grip the floor — every step would send your foot sliding backward with nothing to push against, and you would not be able to walk at all. Vehicle tyres would spin uselessly on the road. Your pen would not "catch" against the paper to write. Even holding a cup of tea would become impossible, because your fingers rely on friction to grip its surface. Far from being a nuisance, friction is one of the most quietly essential forces in daily life — it just rarely gets credit because it is not dramatic like gravity or electricity.

6.4 Newton's First Law of Motion

Newton's first law of motion can be stated as:

Newton's First Law

An object at rest remains at rest, and an object in motion continues to move with a constant velocity, unless a net force acts upon the object.

In other words: if the net force acting on an object is zero, the object cannot begin to move, nor can it change its velocity. Its acceleration in that case is zero.

Note

"At rest" means zero velocity. "Constant velocity" means no change in either the *magnitude* or the *direction* of velocity — if this constant velocity is non-zero, the object moves in a straight line, at the same speed, indefinitely (in the absence of a net force).

Everyday Connection: The Lurch on the E-Scooter (Revisited)

Return to the Opening Wonder. You were moving forward at the same speed as the e-scooter. The instant your friend braked, the scooter's velocity dropped sharply — but *your* body, having no force acting on it to slow it down at the same rate, tried to continue moving forward at its original speed. That is Newton's first law in action: your body was "in motion" and tended to "continue in motion" until the friction of your grip and your own muscles supplied the force to slow you down too.

This is precisely why seatbelts, headrests, and grab-handles in buses exist — they are engineering solutions to a law of physics, not just safety add-ons.

Worked Example 6.2 — Redeveloped: The Delivery Cart That Won't Slow Down

Original book version: A person exerts a forward force on a moving box that exactly equals the force of friction opposing it. Will the box keep moving or come to rest?

Everyday Version: A delivery boy is pushing a loaded thela (handcart) down a lane at a steady pace. He is applying a forward force that is exactly equal in magnitude to the force of friction between the cart's wheels and the road. Will the cart continue moving, or gradually stop?

Answer: The force of friction acts backward on the cart. Since the push and the friction are equal in magnitude and opposite in direction, they balance each other exactly. The **net force on the cart is zero**. By Newton's first law, the cart will continue moving with **constant velocity** — neither speeding up nor slowing down.

Worked Example 6.3 — Redeveloped: Graphing a Coasting Skater

Everyday Version: Picture an ice-skater at Gulmarg's skating rink gliding on perfectly smooth ice with no one pushing her — so no net force acts on her. Sketch (i) her position-time graph, and (ii) her velocity-time graph.

Answer: When no net force acts on an object, exactly two situations are possible — the object is at rest, or it moves with constant velocity.

If the skater were at rest, her position would never change with time — a **flat horizontal line** on the position-time graph, and a **flat line at zero** on the velocity-time graph.

Since she is gliding at constant velocity instead, her position-time graph is a **straight line with a constant (non-zero) slope**, and her velocity-time graph is a **flat horizontal line at a non-zero value** — because her velocity is neither increasing nor decreasing.

Pause and Ponder:

1. An object is moving with a constant velocity. Is there a net force acting upon it?
2. Suppose no net force acts on an object. Which of the following are possible: (i) it remains at rest if it was at rest; (ii) it keeps moving at constant velocity if it was already moving; (iii) it moves with constant acceleration?
3. In the real world, it is difficult to find a situation where absolutely no forces act on an object. But by applying additional forces, we can still achieve a condition where the *net* force is zero. Explain this with an example — for instance, how does Example 6.2's delivery cart achieve zero net force despite friction constantly acting on it?

6.5 Newton's Second Law of Motion

You already know that a force can set an object in motion, bring it to rest, or change its velocity. A change in velocity means the object is *accelerating*. So a force produces acceleration. But exactly how are net force, mass, and acceleration related?

Think as a Scientist

From everyday experience, a gentle push on a ball produces a slow start (small acceleration); a hard push produces a fast start (large acceleration). This gives us a hypothesis: **for the same object, a larger force produces a larger acceleration.** How could you test this rigorously — applying different, precisely known forces to the same object on the same surface, and measuring the resulting acceleration each time?

Activity 6.3 — Redeveloped: Racing a Shoebox Cart

Original book version: Build a small cart from a cardboard box, pencils (as axles), and ball-bearing wheels. Pull it using a thread passed over a pulley, with a paper cup of coins hanging off the end providing a constant force via gravity. Record its motion on slow-motion video for two different hanging masses, and compare accelerations.

Everyday Version (Demonstration Activity): Build a simple cart from an empty shoebox, two pencils as axles, and four small wheels (bottle caps or bangles with a hole punched through work well too). Tie a thread to the front of the cart, run it over a pulley (a piece of PVC pipe fixed at your study table's edge works fine), and hang a paper or plastic cup from the other end.

1. Place a few ₹1 or ₹5 coins in the cup. Weigh the cup with the coins on a kitchen scale.
2. Mark a start line for the cart. Record a slow-motion video on your phone as you release the cart, until it reaches the pulley end.
3. From the video, read off the time taken, T_1, for the cart to travel the fixed distance s.
4. Now double the coins (and hence the hanging weight) in the cup, and repeat, recording the new time T_2 for the same distance s.

Since the cart starts from rest (u = 0) both times and travels the same distance s, the kinematic equation gives:

$$s = \tfrac{1}{2}\, a_1 T_1^2 \quad \text{and} \quad s = \tfrac{1}{2}\, a_2 T_2^2$$

Equating these:

$$a_1 / a_2 = T_2^2 / T_1^2$$

Substituting your measured values of T_1 and T_2, you should find that doubling the force (the hanging weight) **increased the acceleration** of the cart. This confirms our hypothesis: for a fixed mass, acceleration increases as the applied net force increases.

Think as a Scientist

Does acceleration depend on anything besides force? From experience, it is easier to set a light school bag in motion than a heavy steel trunk, even with the same push. This suggests a second hypothesis: **for the same force, a smaller mass produces a larger acceleration.** How would you test this?

Activity 6.4 — Redeveloped: Loading the Cart Instead

Everyday Version (Demonstration Activity): Repeat Activity 6.3, but this time keep the hanging cup and coins constant, and instead double the mass of the shoebox cart itself (by adding books or weights inside it). Weigh the cart before and after using the kitchen scale, and record the new travel time.

You should find that with the same applied force, doubling the cart's mass **decreased its acceleration**. This means: for a given force, acceleration is **inversely** related to mass.

Thread of Curiosity: Why Your Numbers Won't Be Exact

According to the relation above, doubling the force in Activity 6.3 should have exactly doubled the acceleration — but in practice, you likely measured an increase a little short of double. Similarly, in Activity 6.4, doubling the mass should have exactly halved the acceleration, but your measured ratio was probably slightly off too. Besides ordinary measurement error, the friction between the cart's wheels and the table surface is working against you the whole time — a real-world complication the simple model deliberately leaves out.

The relationship between force, mass, and acceleration is expressed in **Newton's second law of motion**, one of the most fundamental ideas in all of science:

Newton's Second Law

When a net force acts on an object, the object accelerates in the direction of the net force. The magnitude of the acceleration is proportional to the magnitude of the net force, and inversely proportional to the mass of the object.

Mathematically:

$$a = F / m \qquad ...(6.1)$$

$$\text{or} \quad F = ma \qquad ...(6.2)$$

where a denotes acceleration, F denotes net force, and m denotes the mass of the object. The direction of acceleration is always the same as the direction of the net force.

The SI units of mass and acceleration are kg and m s^{-2} respectively. If m = 1 kg and a = 1 m s^{-2}, then from Eq. (6.2):

$$F = (1 \text{ kg}) \times (1 \text{ m s}^{-2}) = 1 \text{ kg m s}^{-2} = \mathbf{1\ N}$$

One newton is defined as the force that produces an acceleration of 1 m s^{-2} on an object of mass 1 kg.

Thread of Curiosity: What Does 1 Newton Actually Feel Like?

Hold a 100 g packet of biscuits, or a small 100 g pack of namkeen, flat on your palm. The upward force your palm applies to hold it steady against gravity is about **1 N**. The next time someone asks you to "imagine a newton," you now have it sitting in your hand.

Under gravity, a falling object accelerates towards the Earth with the **acceleration due to gravity**, denoted g. Using Eq. (6.2), the gravitational force on an object of mass m (its weight) is:

$$F = mg \qquad ...(6.3)$$

The value of g is 9.8 m s^{-2} near the Earth's surface, and can be taken as nearly constant there. For quick estimates, g = 10 m s^{-2} is often used.

Note

The acceleration due to gravity, g, does **not** depend on the mass of the object — a coin and a cricket ball, dropped together in a vacuum, fall with exactly the same acceleration.

6.5.1 The Complete Picture: Momentum

Force can also be expressed through a related quantity called **momentum**. The momentum of an object is defined as the product of its mass and velocity:

$$p = mv$$

Momentum has the same direction as velocity, and its SI unit is kg m s^{-1}.

Ready to Go Beyond: Newton's Second Law, in Full

The more complete and general form of Newton's second law is expressed in terms of momentum: **the rate of change of momentum of an object is proportional to the net force acting on it, and takes place in the direction of that net force.** Written this way, the law applies even to situations where the object's mass is *not* constant — a case where $F = ma$ alone breaks down.

This matters enormously for a rocket. As a rocket burns fuel and expels exhaust gas, its own mass keeps decreasing every second. $F = ma$ cannot

cleanly describe this changing-mass system — but the momentum form of the second law handles it without any trouble. This is one reason momentum, not just $F = ma$, is considered the deeper and more fundamental statement of the law.

Newton's second law explains many everyday events that would otherwise seem mysterious.

Everyday Connection: The Soft Hands of a Great Fielder

Watch any international cricket match closely: when a fielder catches a fast, hard-hit ball, their hands do not stay rigid at the moment of contact. Instead, they gradually pull their hands backward, moving with the ball just after catching it — the way Ravindra Jadeja or any elite fielder is trained to do. This increases the *time* over which the ball's high velocity reduces to zero.

From $F = ma$, and knowing that acceleration is the rate of change of velocity, a **longer stopping time means a smaller acceleration** for the same total change in velocity. A smaller acceleration needs a smaller force from the fielder's hands to stop the ball — which both saves the catch and saves the fielder's fingers from injury.

Everyday Connection: The Airbag in an Accident

For exactly the same reason, cars are fitted with airbags. In a collision, when the vehicle stops abruptly, the airbag inflates in milliseconds into a soft, compressible cushion. Instead of the passenger's head and chest hitting the hard steering wheel or dashboard instantly, they push into the bag, and the time over which the velocity drops to zero is stretched out. A longer stopping time means smaller acceleration, which means a smaller force on the passenger's body — reducing the risk of serious injury, especially when combined with a seatbelt.

Everyday Connection: Cracking a Coconut in One Go

Now consider the opposite situation. Ever seen someone crack open a fresh coconut in a single hit by throwing it hard onto the ground? The coconut is moving at high velocity, and it stops almost instantly when it hits the hard floor — an extremely *short* stopping time. By $F = ma$, a very short time to change velocity requires a very **large** force from the ground on the coconut. It is precisely this large force that shatters the shell.

Everyday Connection: Mirabai Chanu's Barbell

Saikhom Mirabai Chanu, the weightlifter from Manipur who won the silver medal in the 49 kg category at the Tokyo 2020 Olympics, holds barbells loaded with tens of kilograms perfectly steady above her head. To do this, she must apply an upward force exactly equal to the barbell's weight — a direct, high-stakes application of Newton's second law, performed under an Olympic spotlight.

Worked Example 6.4 — Redeveloped: How Hard Is Mirabai Chanu Really Pushing?

Original book version: A weightlifter holds a barbell steady with 10 kg fixed on each side, and a 10 kg bar. How much force must she apply?

Everyday Version: A weightlifter is holding a barbell steady above her head — 10 kg of plates fixed on each side, and the bar itself weighing 10 kg. How much force is she applying to keep it steady?

Answer: Total mass of the barbell = 10 + 10 + 10 = **30 kg**.

Gravitational force pulling the barbell down (Eq. 6.3):

$$F = mg = 30 \text{ kg} \times 9.8 \text{ m s}^{-2} = \mathbf{294 \text{ N}}$$

To hold the barbell steady (zero acceleration, by Newton's first law), she must apply an equal and opposite force. **She is applying 294 N upward** — for comparison, roughly the weight of three grown adults.

Worked Example 6.5 — Redeveloped: Rahul's Canteen Trolley

Original book version: A student tries to push a stationary 25 kg block on a horizontal floor, where the maximum frictional force opposing motion is 50 N. Find displacement in 2 s for pushing forces of (i) 50 N and (ii) 55 N.

Everyday Version: Rahul is trying to push a stationary canteen trolley loaded with tiffin boxes, of total mass 25 kg, across the school corridor. The maximum force of friction opposing the trolley's motion is 50 N. Find the trolley's displacement in 2 seconds if Rahul pushes with a constant force of (i) 50 N, and (ii) 55 N.

(i) With 50 N: Rahul's push exactly equals the opposing friction. The two forces balance, net force is zero, and by Newton's first law, **the trolley stays exactly where it is.**

(ii) With 55 N:

$$\text{Net force} = 55 \text{ N} - 50 \text{ N} = 5 \text{ N}$$

Using Newton's second law:

$$a = F/m = 5 \text{ N} / 25 \text{ kg} = 0.2 \text{ m s}^{-2}$$

Using the kinematic equation $s = ut + \frac{1}{2}at^2$ with $u = 0$:

$$s = 0 \times 2 + \tfrac{1}{2} \times 0.2 \times (2)^2 = \mathbf{0.4 \text{ m}}$$

The trolley moves 0.4 m forward in those 2 seconds.

Worked Example 6.6 — Redeveloped: A Sports Car at the Buddh International Circuit

Everyday Version: A sports car of mass 1500 kg is moving east on a test track (imagine the Buddh International Circuit near Greater Noida). Its velocity-time graph shows: a straight-line rise from 0 to 10 m s^{-1} during 0–5 s; a flat line at 10 m s^{-1} from 5–10 s; and a straight-line fall from 10 m s^{-1} to 0 during 10–15 s. Find the force acting on the car in each interval.

(i) 0 s to 5 s: The graph is a straight, rising line, so the car has constant acceleration, with $u = 0$, $v = 10$ m s^{-1}, $t = 5$ s. Using $v = u + at$:

$$10 = 0 + (a \times 5) \implies a = 2 \text{ m s}^{-2}$$

$$F = ma = 1500 \text{ kg} \times 2 \text{ m s}^{-2} = \textbf{3000 N, acting east.}$$

(ii) 5 s to 10 s: The graph is flat (constant velocity), so acceleration is zero. **No net force acts on the car.**

(iii) 10 s to 15 s: The graph is a straight, falling line, with $u = 10$ m s^{-1}, $v = 0$, $t = 5$ s.

$$0 = 10 + (a \times 5) \implies a = -2 \text{ m s}^{-2}$$

$$F = ma = 1500 \text{ kg} \times (-2 \text{ m s}^{-2}) = \textbf{−3000 N}$$

The negative sign shows the force acts **opposite** to the direction of motion — that is, **3000 N acting west** (the braking force).

Pause and Ponder:

1. A toy car of mass 100 g moves with a constant velocity of 0.5 m s^{-1}. What is the net force acting on it?
2. Two children of different masses sit on identical park jhoolas (swings). To give both of them the same initial acceleration, for which child would you need to apply a larger force? Explain why.
3. How does bubble wrap or hay protect glass items — like framed photos or glass bangles — during transport by train or truck?

6.6 Newton's Third Law of Motion

We have so far described what happens to a single object when a net force acts on it. But do you recall learning that at least *two* objects must interact for a force to exist at all? Haven't you felt, when you kick a football, that the ball also pushes back against your foot? It is natural to ask: how are *both* objects affected in this interaction? Newton's third law answers exactly this.

Activity 6.5 — Redeveloped: The Spinning Office Chair

Everyday Version: Sit on an office chair with wheels (or a gaming chair), lifting your feet off the ground. Using both hands, push a heavy study table away from you. What happens to you? Does the chair roll backward? Now instead try pulling the table towards you. Which direction does the chair move this time?

Each time you apply a force on the table, the table applies an equal force back on you, in the **opposite** direction — pushing you (and your chair) backward when you push the table forward, and pulling you forward when you pull the table towards you.

This is also exactly how you move a bicycle forward without pedalling — you push the ground backward with your feet, and the ground pushes your feet (and you, and the bicycle) forward with an equal and opposite force. It is, in fact, how you walk or run at all: your feet push the ground backward, and the ground's reaction — friction — pushes you forward. Here, friction is *helping* your motion rather than opposing it.

Everyday Connection: Wet Floors, Grooved Soles, and Monsoon Slips

If there were no friction between your foot and the ground, your foot would simply slide backward as you tried to push off, and you would fall — exactly what happens on a wet, polished floor during the monsoon, or on ice. Grooves in the soles of your shoes exist specifically to increase this frictional grip, just as the treads on vehicle tyres increase grip with the road. This is precisely why driving on a rain-soaked or waterlogged road is so much riskier than on a dry one.

Activity 6.6 — Redeveloped: The Railway Platform Spring-Balance Duel

Everyday Version: Take two identical spring balances (or luggage scales, the kind coolies use at railway platforms). Connect their hooks together and lay them flat on a table. Fix the far end of one balance to an immovable object, or have a friend hold it firmly. Now pull the free end of the other balance with varying force, and read both scales each time.

You will find the two readings are **always identical**, no matter how hard you pull. This confirms Newton's third law directly: the force you exert on the fixed balance and the force it exerts back on you are always equal in magnitude.

Newton's third law can be stated as:

Newton's Third Law

Whenever one object exerts a force on a second object, the second object simultaneously exerts an equal and opposite force on the first object.

Note

These forces always occur in **pairs** — but remember, the two forces in the pair act on **two different objects**, so they never cancel each other out.

Everyday Connection: Climbing a Coconut Tree

You may have seen someone climb a tall, straight coconut or palm tree along the Kerala or Konkan coast. The climber's legs push down and inward against the trunk, and the friction between their legs and the bark pushes them upward with an equal force. This is why it is far harder to climb a smooth-barked trunk with less friction than a rough one — the "reaction" force that pushes the climber up simply is not strong enough.

Everyday Connection: The Canoe Paddle (Answering the Opening Question)

Remember the canoe question from the very start of this chapter: why does a canoe move forward when the paddler pushes water backward? Here is the full answer. When the canoeist pushes the paddle backward against the water, the water pushes the paddle **forward** with an equal and opposite

force. These two forces act on different objects — the paddle and the water — so they do not cancel. The forward force on the paddle (and hence the canoe, since the paddler is part of the canoe system) is what propels it ahead. Push harder on the water, and the forward reaction force is larger, so the canoe accelerates faster.

Thread of Curiosity

Beyond how hard someone paddles, several other factors — water drag, currents, the mass of the canoe, and rowing style — also affect its speed. Newton's third law explains the *cause* of forward motion, but real-world speed depends on much more.

You have probably watched ISRO rocket launches on television or on YouTube. A rocket lifting off can also be explained using Newton's third law.

Activity 6.7 — Redeveloped: The Balloon Rocket

Everyday Version: Inflate a large balloon and tie its neck temporarily with thread. Tape a plastic drinking straw along its surface, one end pointing toward the neck. Pass a length of thread through the straw and tie both ends tightly between two fixed points (two door handles, or two hooks on opposite walls, work well). Now untie the balloon's neck and let it go — observe which direction the balloon-and-straw shoots.

As the balloon's stretched rubber pushes the trapped air molecules out through the neck, the escaping air pushes back on the balloon with an equal and opposite force — sending the balloon shooting in the direction opposite to the air rushing out.

Everyday Connection: How an ISRO Rocket Actually Lifts Off

A rocket works on exactly the same principle as the balloon. Its engines burn fuel and expel hot exhaust gas downward at very high speed. By Newton's third law, this expelled gas exerts an equal and opposite force **upward** on the rocket. When this upward force exceeds the rocket's weight, the net force is upward, and the rocket lifts off.

This same principle also works in reverse. If a rocket already moving through space fires its engine in the *direction of motion*, the exhaust gases push back against the rocket, slowing it down. This exact manoeuvre — called retro-thrust — was used by the **Vikram lander of Chandrayaan-3** to decelerate from its orbital speed and achieve the slow, controlled descent needed for its historic soft landing near the Moon's south pole in August 2023.

Meet a Scientist: Vikram Sarabhai — Father of the Indian Space Programme

Vikram Sarabhai (1919–1971) was the physicist who founded what would become the **Indian Space Research Organisation (ISRO)**. In 1963, he established the Thumba Equatorial Rocket Launching Station (TERLS) near Thiruvananthapuram, Kerala — India's first rocket launch facility — laying the foundation for a space programme that, six decades later, would land the Vikram lander (named in his honour) near the Moon's south pole. Every ISRO launch since has depended on the same Newton's third law you have just

studied.

Note

The pair of equal and opposite forces described by Newton's third law acts on **two different objects**, so they do not balance each other. This is different from two equal and opposite forces acting on the *same* object, which *do* balance (as in Section 6.2).

Is Newton's third law limited to forces that involve physical contact? No — it applies equally to **non-contact** forces, such as magnetic and electrostatic forces. Two bar magnets exert equal and opposite magnetic forces on each other; two similarly charged balloons (the kind you rub on your hair on a dry day, and which then repel each other) exert equal and opposite electrostatic forces on each other too.

Worked Example 6.7 — Redeveloped: The Mango That Falls (and the Earth That Doesn't)

Original book version: The Earth and a fruit apply equal and opposite gravitational forces on each other. Why does the fruit fall towards the Earth, while the Earth doesn't seem to move towards the fruit?

Everyday Version: In many parts of the world, this story is told with an apple falling near Newton. In India, it might as well be a **ripe mango** falling from a tree in your grandmother's courtyard. The Earth and the mango pull on each other with equal and opposite gravitational forces. So why does the mango fall towards the Earth, while the Earth shows no visible motion towards the mango?

Answer: Though the forces on both the Earth and the mango are equal in magnitude, the Earth's mass is enormously larger than the mango's. From $a = F/m$, the same force produces a vastly smaller acceleration on a vastly larger mass. The Earth's resulting acceleration is so minuscule that it is utterly unnoticeable, while the mango's acceleration (about 9.8 m s^{-2}) is dramatic enough to bring it crashing onto the ground.

Worked Example 6.8 — Redeveloped: The Recoil of an Air Gun at a Mela

Original book version: A 0.1 kg bullet is fired from a 5 kg gun with a force of 2 N. Find the initial accelerations of the bullet and the gun.

Everyday Version: At the balloon-shooting stall of a Diwali mela, an air gun of mass 5 kg fires a 0.1 kg pellet with a force of 2 N, causing the gun to recoil (kick back) in your hands. What are the initial accelerations of the pellet and the gun?

Answer: By Newton's third law, the recoil force on the gun is also 2 N (equal and opposite to the force on the pellet).

Acceleration of the gun:

$$a = F/m = 2\ \text{N} / 5\ \text{kg} = \mathbf{0.4\ m\ s^{-2}}$$

Acceleration of the pellet:

$$a = F/m = 2 \text{ N} / 0.1 \text{ kg} = \mathbf{20 \text{ m s}^{-2}}$$

Even though the pair of forces is equal in magnitude, the accelerations are wildly different — because the masses being accelerated are different. This is why the gun merely "kicks" gently in your hand, while the tiny, light pellet shoots forward fast enough to burst a balloon.

Pause and Ponder:

1. Why does a firefighter sometimes struggle to hold steady the hose issuing a powerful jet of water?
2. A spacecraft is moving through a region of space where the gravitational force on it is negligible. Suggest how it can still change its velocity.

6.7 Forces Acting on a System of Objects

So far, we have applied Newton's three laws to a single object. But can these laws handle two or more objects connected together?

Everyday Connection: Two Trunks Tied Together at the Railway Platform

Picture two steel trunks of masses m_1 and m_2, resting on a smooth railway platform trolley track (frictionless, for simplicity), tied to each other with a rope. A porter pulls the front trunk with a force F. The front trunk pulls the rear trunk via the rope; by Newton's third law, the rear trunk pulls back on the front trunk with an equal and opposite force through the same rope — this internal pulling force is called **tension**, T.

How do we find the acceleration of this two-trunk system?

One approach is to analyse each trunk separately, accounting for the tension acting on each. A **simpler approach** is to treat both trunks and the connecting rope as a **single system**. In this approach, internal forces (like the tension, which trunk 1 and trunk 2 exert on each other) cancel out and need not be considered at all — only external forces acting on the system from *outside* matter. Here, the porter's pull F is the only relevant external horizontal force. Using Newton's second law on the whole system:

$$a = F / (m_1 + m_2) \quad ...(6.4)$$

The two-trunk system accelerates exactly as if it were a single object of combined mass $(m_1 + m_2)$. Had we instead analysed each trunk separately (a method you will learn in higher grades), we would arrive at the identical result — but treating connected objects as a single system is often far simpler.

Ready to Go Beyond

Besides the pull F, the external forces on the two-trunk system also include the combined gravitational force $(m_1g + m_2g)$ acting downward, which is exactly balanced by the combined normal force $(N_1 + N_2)$ from the platform below. These vertical forces balance out, leaving only the horizontal pull F to

determine the system's acceleration.

🧵 Thread of Curiosity

While walking, your arms and legs move in a wonderfully complicated way — yet your overall motion across a room can still be studied by treating your whole body as a single object. Science often becomes dramatically simpler the moment we stop tracking every individual part and start looking at the whole system instead.

Chapter Summary

Concept	Core idea	Everyday example
Force	A push or pull with both magnitude and direction (SI unit: newton, N)	Kicking a football, squeezing a lemon, a spring balance at a fish market
Balanced vs. unbalanced forces	Equal & opposite forces balance (no motion change); unequal forces produce a net force	A tug-of-war rope staying still vs. moving toward the stronger team
Friction	A force opposing relative motion between two surfaces in contact	A carrom striker gliding on a powdered board vs. dragging on a bare one
Newton's First Law (Inertia)	An object at rest stays at rest, and a moving object keeps moving at constant velocity, unless a net force acts on it	Lurching forward when an e-scooter or bus brakes suddenly
Newton's Second Law	Net force = mass × acceleration ($F = ma$); acceleration ∝ force, and ∝ 1/mass	A fielder's "soft hands" reducing catching force; airbags reducing crash impact
Momentum	Momentum $p = mv$; the general form of the 2nd law uses rate of change of momentum, valid even for changing mass	A rocket's mass shrinking as it burns fuel during launch
Newton's Third Law	Every force has an equal and opposite reaction force, acting on a different object	A canoe paddle pushing water back so the water pushes the canoe forward; an ISRO rocket lifting off
Systems of	Connected objects can be	Two railway trunks tied

Concept	Core idea	Everyday example
objects	treated as one system; internal forces (like tension) cancel out	together, pulled as a single combined mass

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Revise, Reflect, Refine — Exercises

Basic Recall

1. State Newton's first, second, and third laws of motion in your own words, and give one everyday Indian example for each.
2. Define momentum. Why is the momentum form of Newton's second law considered more general than $F = ma$?
3. Explain, using the idea of balanced and unbalanced forces, why a rope in a tug-of-war sometimes stays perfectly still and sometimes suddenly swings to one side.

Apply & Think

1. **(Numeric)** During practice for the snake boat race (Vallam Kali) in Kerala, 100 oarsmen row a traditional boat together. 95 of them row backward (to propel the boat forward), but by mistake, 5 row in the opposite direction. If each oarsman applies a horizontal force of 200 N, what is the net force on the boat, and in which direction? (Ignore drag and air resistance.)
2. **(Numeric)** An ace footballer strikes a penalty with a football speed of 108 km h^{-1}. The estimated force imparted to the 0.4 kg ball was 800 N. Using the impulse–momentum idea (Force × time = mass × change in velocity), calculate the time of contact between the footballer's foot and the ball. (Hint: convert 108 km h^{-1} to m s^{-1} first.)
3. A sailor jumps forward from a small boat onto the shore. Will the boat move? If so, in which direction, and why? Now explain, using the same reasoning, why a canoe lurches backward slightly when a passenger jumps off the front.

Creative Design Challenges

1. **The Anti-Skid Challenge:** Indian roads flood quickly in the monsoon, and braking distances increase sharply. Design (sketch and describe) a shoe sole, tyre tread, or road-surface texture that could reduce the danger of low friction in wet conditions. Explain the physics behind your design.
2. **The Impulse Comic Strip:** Create a 4–6 panel comic strip explaining Newton's second law using a moment from a sport you enjoy — a badminton smash, a kho-kho tag, a kabaddi raid, or a cricket catch. Show clearly how time of contact affects force in your chosen moment.
3. **The Friction Detective:** Design a simple, doable-at-home experiment (different from Activities 6.1 and 6.2) to test whether the force of friction

changes when you increase how hard two surfaces press against each other (i.e., increase the normal force). Predict your result before testing it.

4. **AI Creative Spark — Newton in 2050:** Imagine an autonomous flying taxi navigating over an Indian city in 2050. List three situations in its flight where its onboard computer must apply Newton's three laws in real time to keep passengers safe and comfortable. What sensors might it need to measure force, mass, and acceleration continuously?

Journey Beyond — Going Deeper

Challenge A: The Capstan Effect

Wrap a rope once around a rough tree branch, a gate post, or a wooden railing. Tie a heavy bucket of water to one end, and try to hold the other end steady. Now add one more turn of rope around the post and repeat. You should find that each extra turn dramatically increases the "grip" between rope and post, sharply reducing the force you need to apply to hold the same load — often by far more than you'd expect from just one extra turn.

Investigate and explain: why does friction increase so dramatically, rather than in a simple straight-line way, with each additional turn? This same principle — called the capstan effect — is what allows a single sailor to hold a massive ship steady at a port like Mumbai or Kandla using rope wound around a mooring bollard.

Challenge B: Racing Magnetic Toy Cars

Take two toy cars of equal mass and fix a small bar magnet on top of each, so that their like poles face each other. Set them near the midpoint of a smooth metre-scale track, and release them simultaneously. Using two stopwatches (or your phone's slow-motion camera), record the time taken and distance travelled by each car before it comes to rest. Repeat after adding equal extra masses to both cars.

Do the two cars always travel equal distances in opposite directions? Plot a graph of distance travelled versus mass added, and connect your findings back to Newton's third law and to what you know about force, mass, and acceleration.

Challenge C: Estimating an E-Rickshaw's Launch Force

E-rickshaws are now a common sight on Indian roads. Estimate the net forward force an e-rickshaw carrying a driver and three passengers would need, to accelerate from rest to 15 km h^{-1} in about 5 seconds. Research (or reasonably estimate) the typical mass of an e-rickshaw plus its passengers, show every assumption you make, and calculate your answer using Newton's second law. Compare your estimate with the actual motor power ratings of e-rickshaws sold in India, and check if your answer is in a sensible range.

Happy Exploring! Every force you feel, apply, or resist today is Newton's three laws quietly at work.